

Nano and Biological Technology Panel: Quantum Information Science

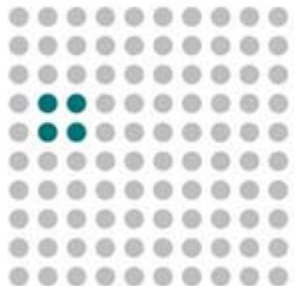
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NSW Manager, Centre for Quantum Computer Technology

NSW Director, Australian National Fabrication Facility

School of Electrical Engineering & Telecommunications

The University of New South Wales



CENTRE FOR
QUANTUM COMPUTER
TECHNOLOGY

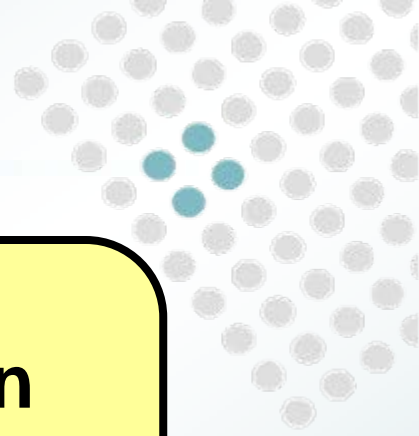
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Quantum Information Science



Data Security

National Security
Financial Services
e-Commerce

Decryption

National Security
Intelligence


Killer Apps

Supercomputers

Database Searching
Bioinformatics
Modeling & Design

Semiconductors

Integrated Circuits
Sensors
Nano-structuring

Outline

- Quantum Computing & Communications

Science fiction becomes science fact ...

- Single Atom & Single Photon Nanotechnologies

Plenty of room at the bottom ...

- Future q -IT Applications

What could be possible?

- Visualizing a Quantum Computer of the Future

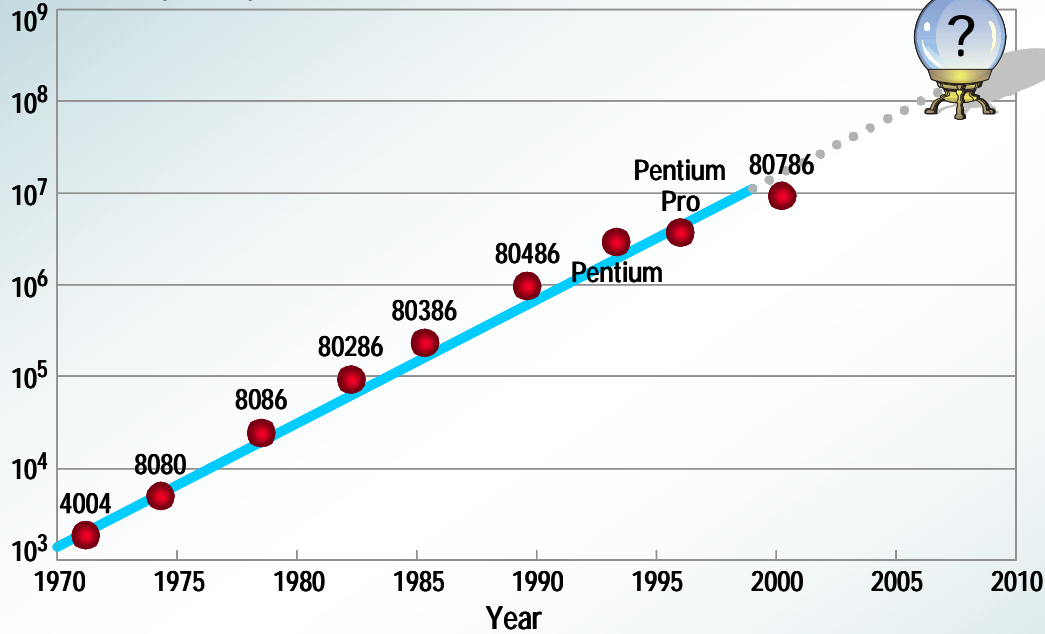
Computing at the atomic level ...



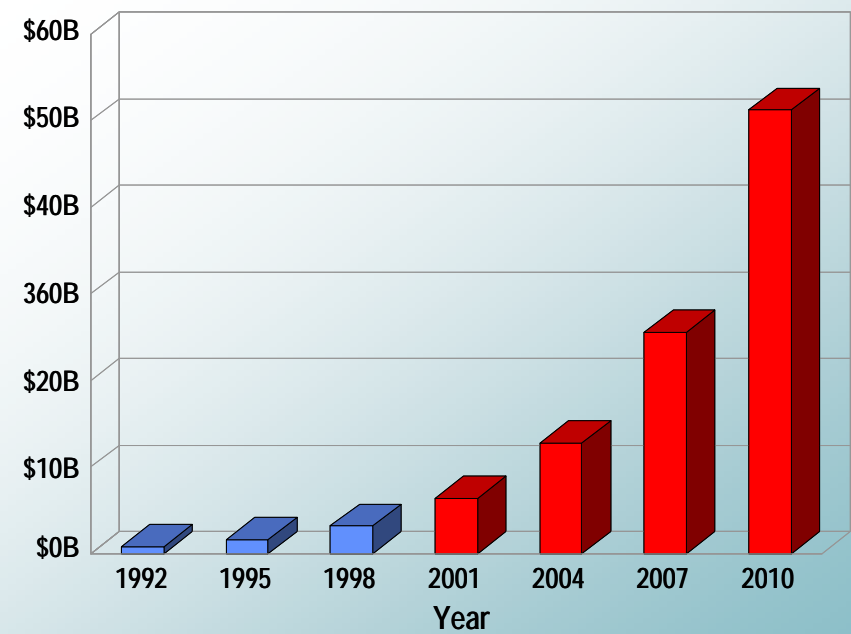
Conventional computing ...

... must confront some serious issues

Transistors per chip



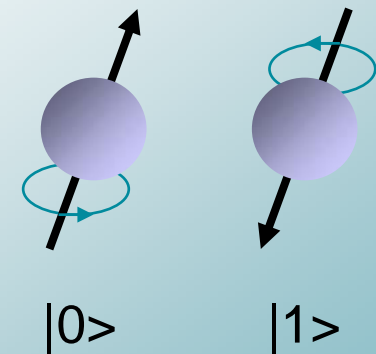
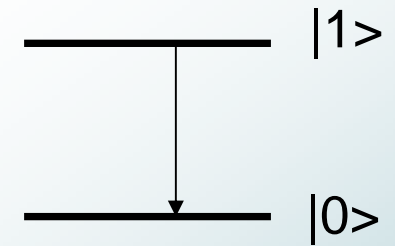
Cost of Fab



Quantum computing

... could well be the solution

Conventional Computer	Quantum Computer
0, 1	$ 0\rangle, 1\rangle$
bits	qubits Quantum state of a two-level system

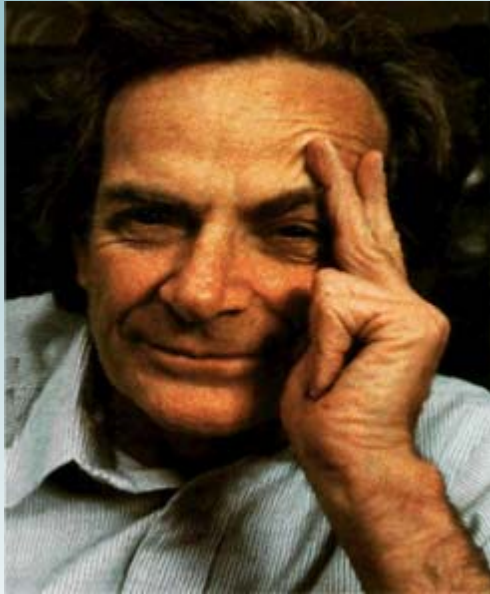


The power of quantum superposition ...

Ever wished you could be in two places at the same time ?

- Consider a **300 qubit** byte of information
- $x = b_{300}b_{299} \dots b_3b_2b_1$
- Example: $x = 100110100\dots110011010$
- Possible states = 2^{300} = **Number of atoms in universe!!!**
- A QC would compute with all of these in parallel
- Blue Gene: 10^{15} ops/sec would take **10^{78} years** to look at each

From basic science...



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981



Algorithms for quantum computation:
discrete logarithms and factorings (1994)

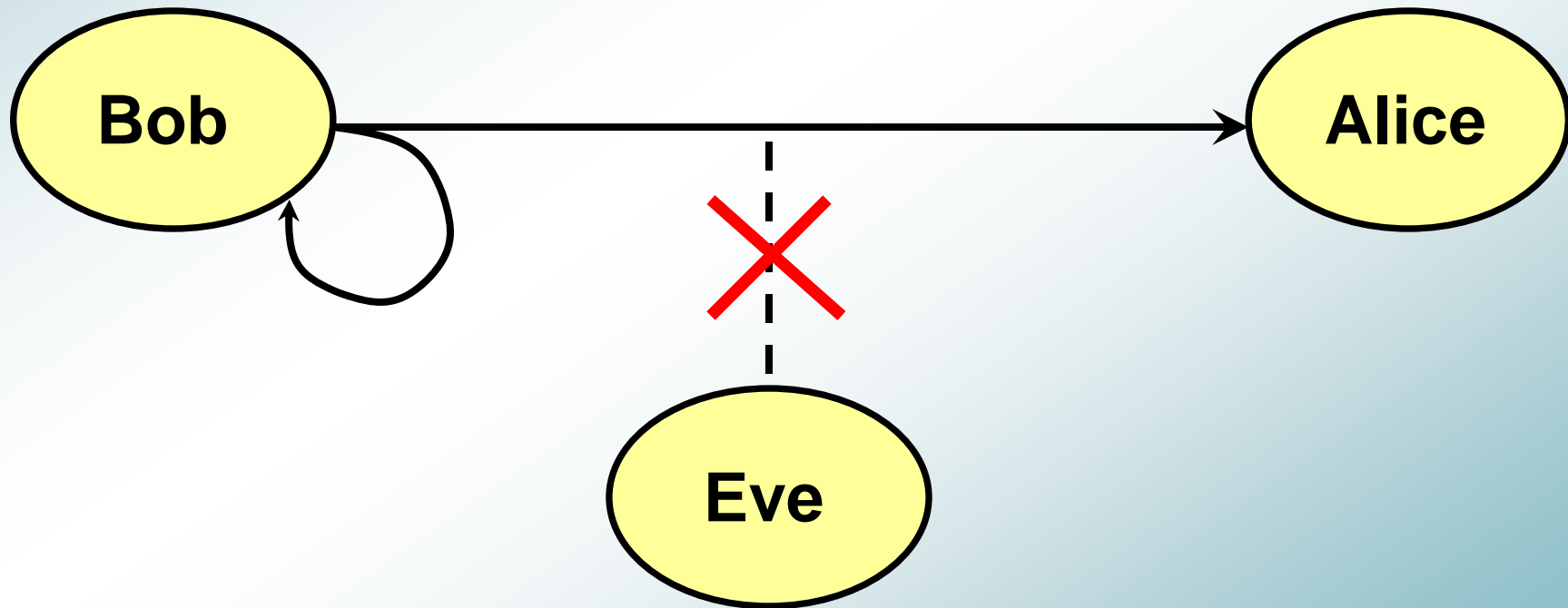
...to new technologies....



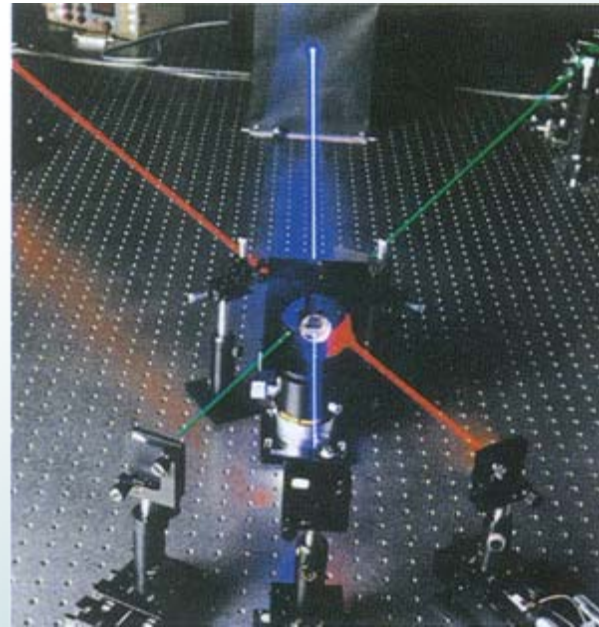
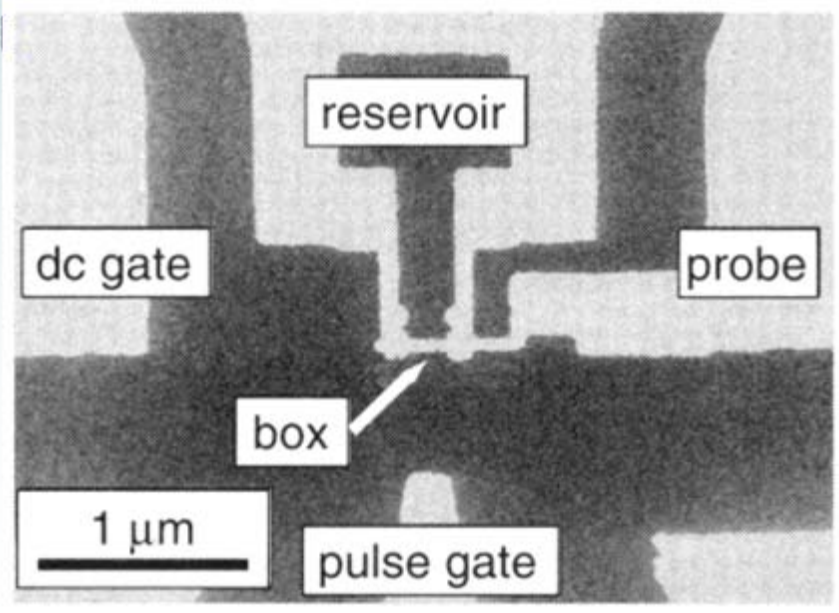
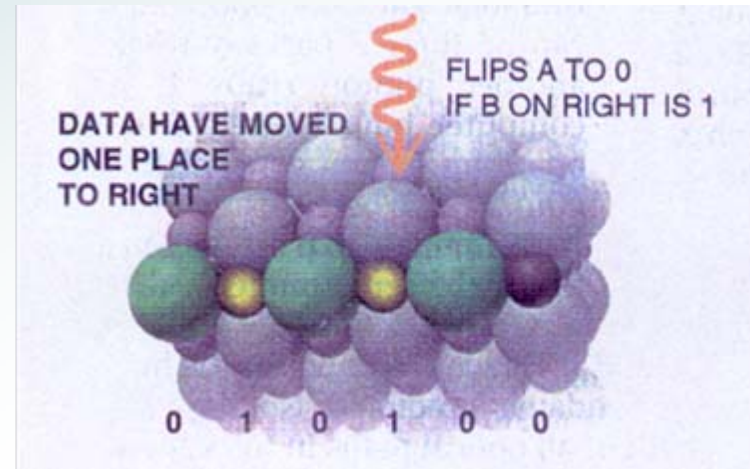
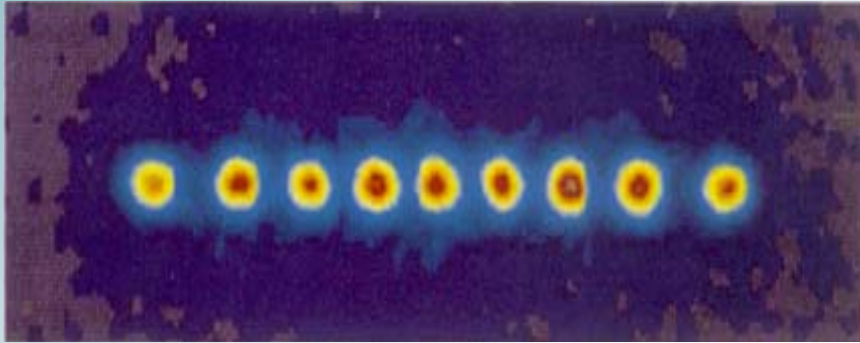
...quantum technologies

Quantum Communications

... when ***absolute*** security of information is vital...



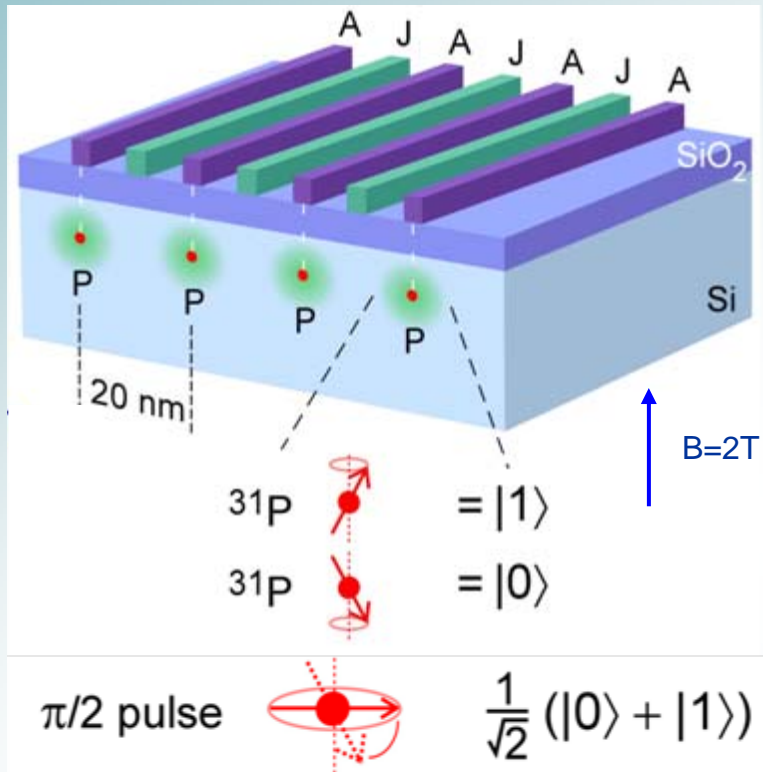
The first quantum computers ...



Australia-US Partnership in QC

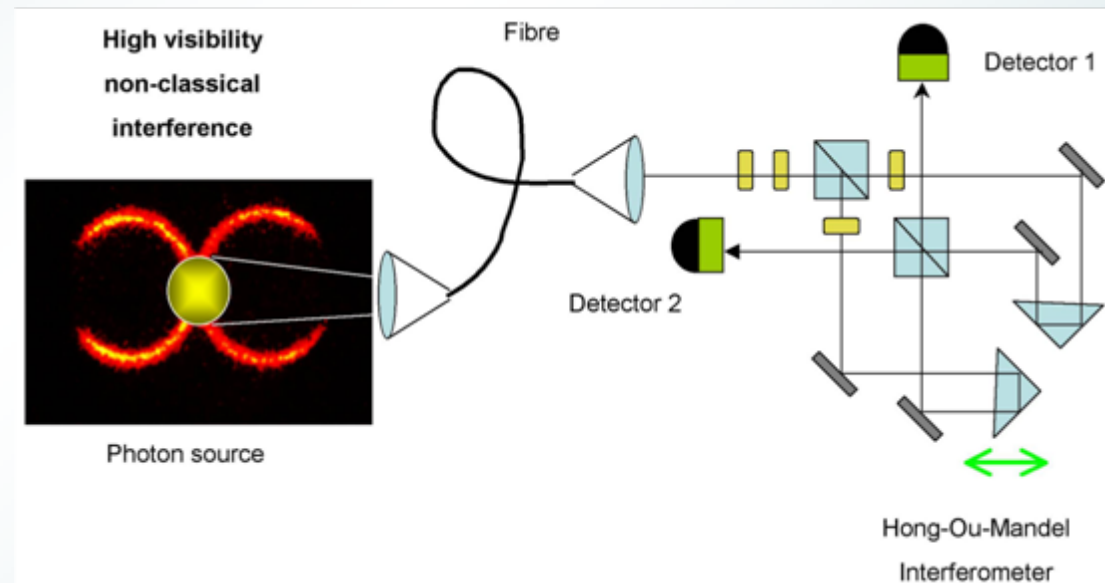
Silicon Solid State QC

Single Atom Nanoelectronics

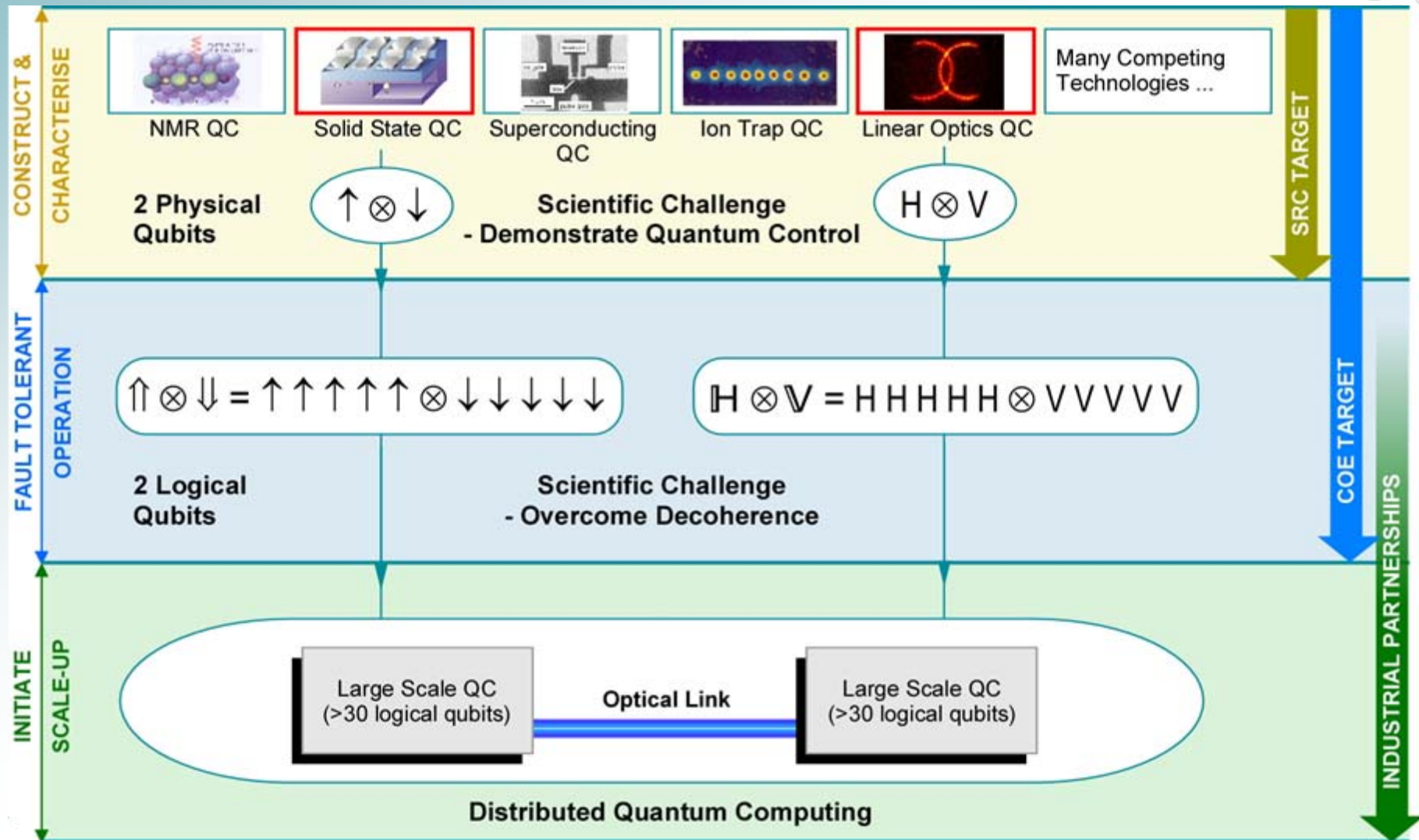


Linear Optics QC

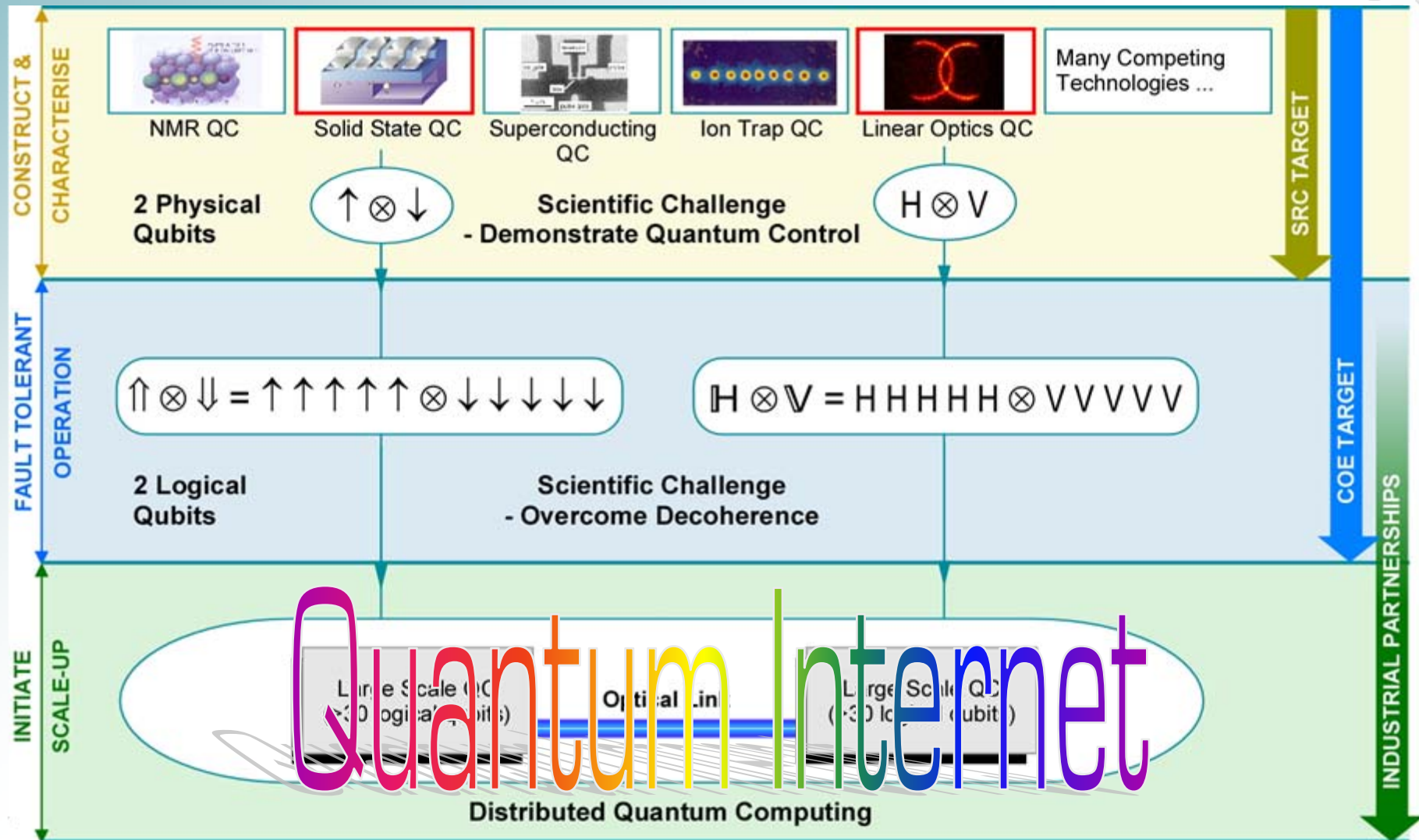
Single Photon Photonics



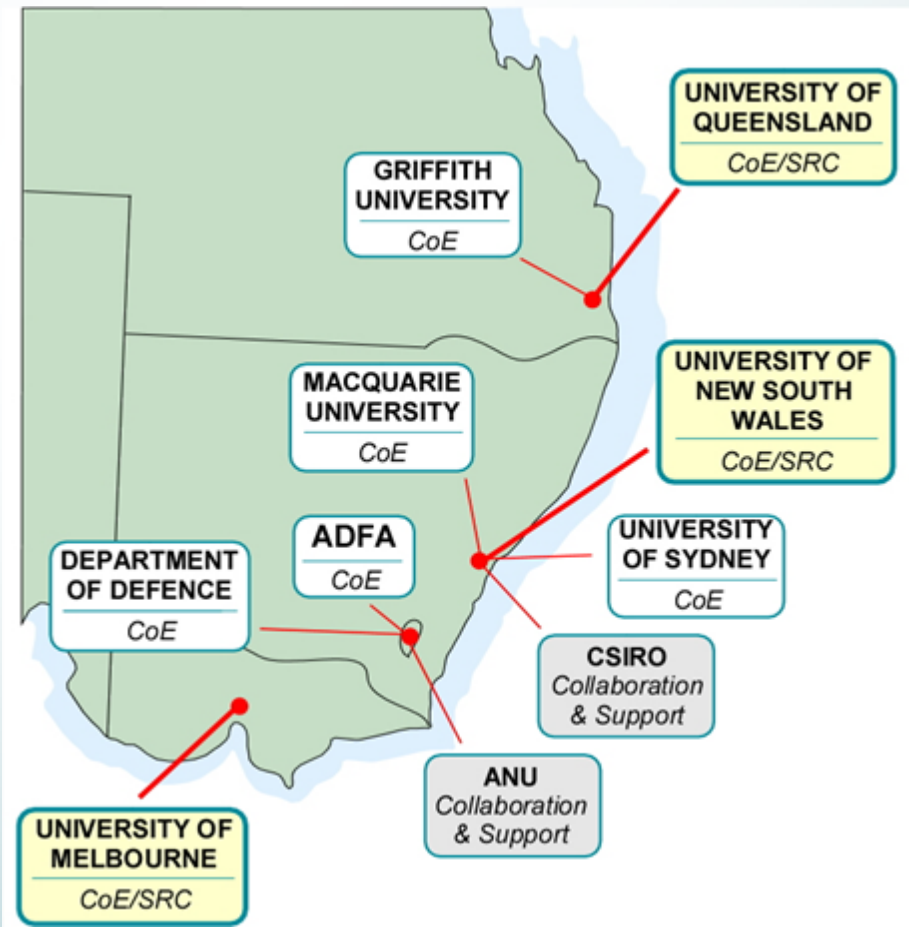
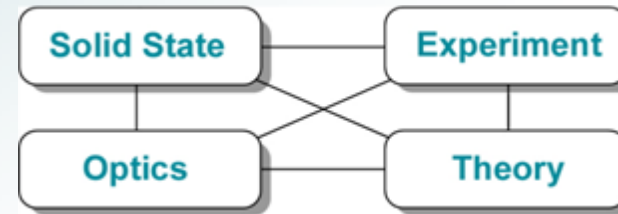
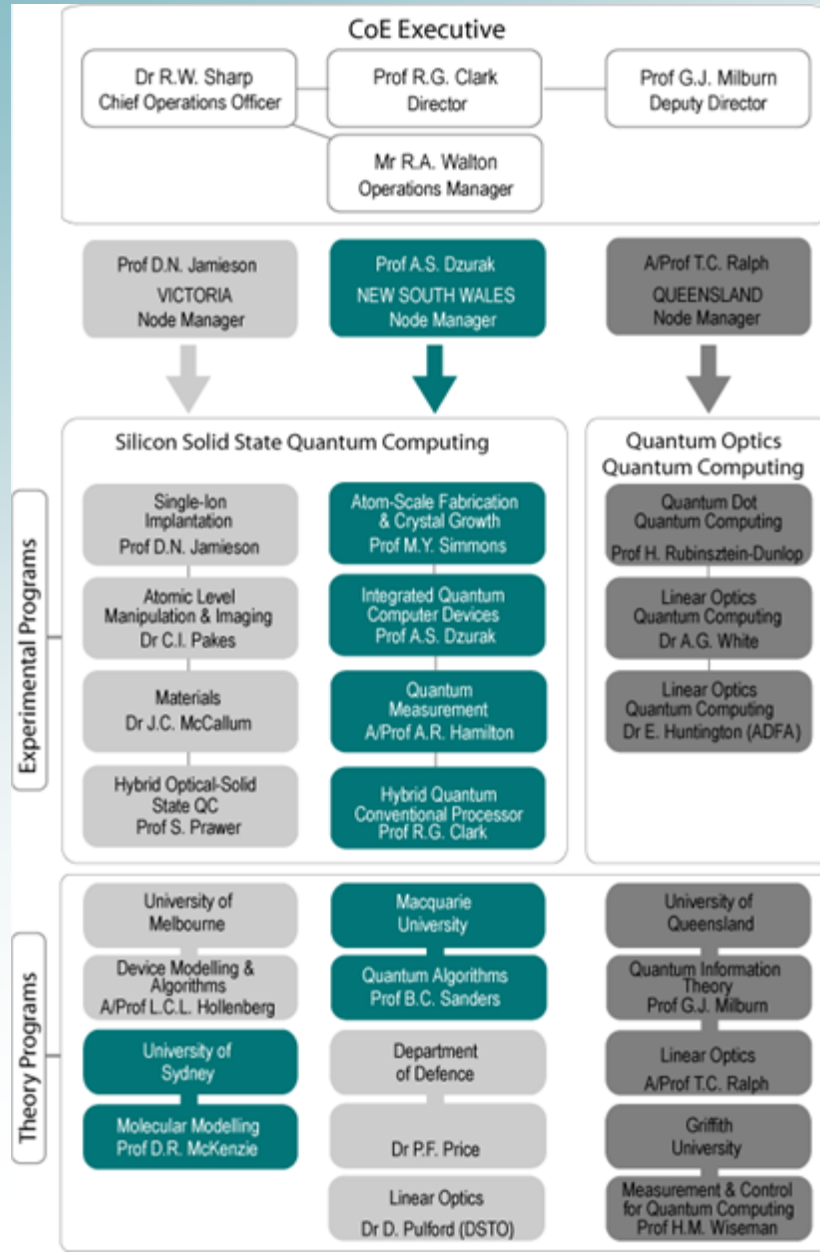
Computing + Communications =



Computing + Communications =



Australian Research Council Centre of Excellence for Quantum Computer Technology

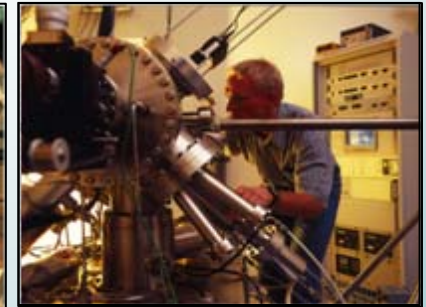
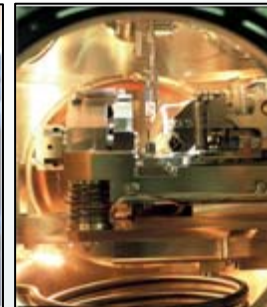


Underpinning Nanotechnologies

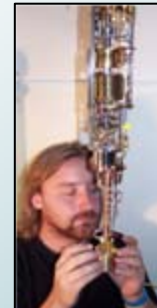
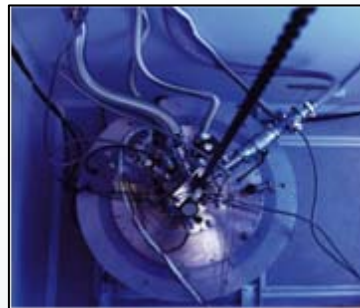
Nano-scale Fabrication



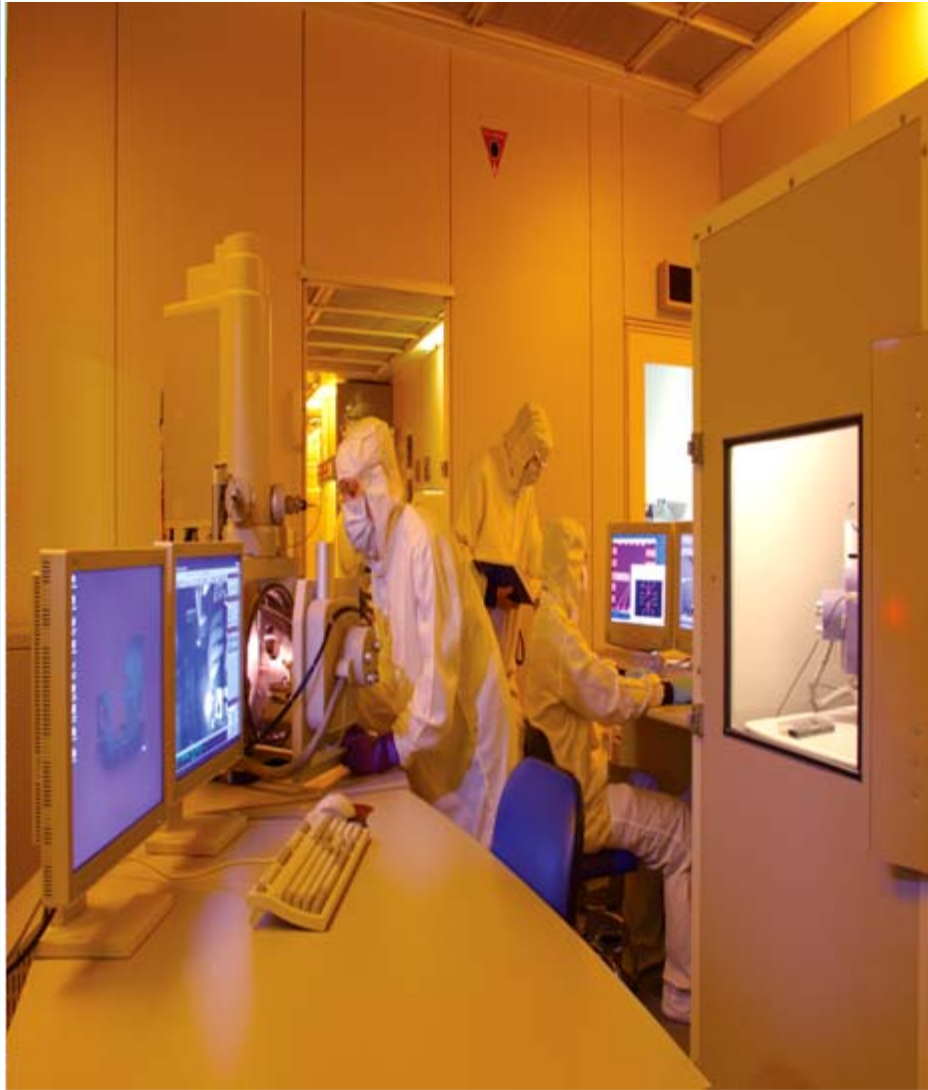
Atom-scale Fabrication



Quantum Measurement



Single Atom Nanoelectronics : Top Down

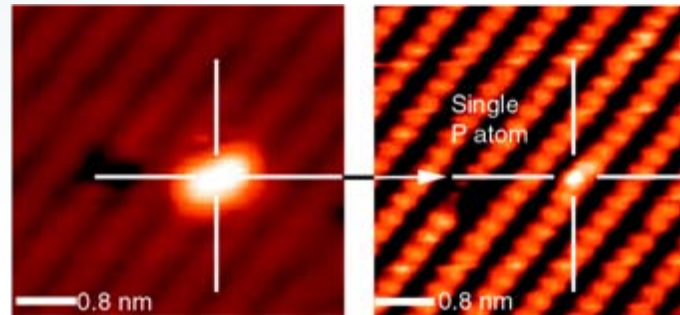
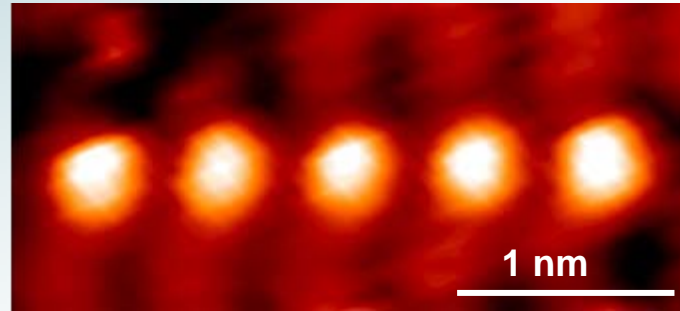
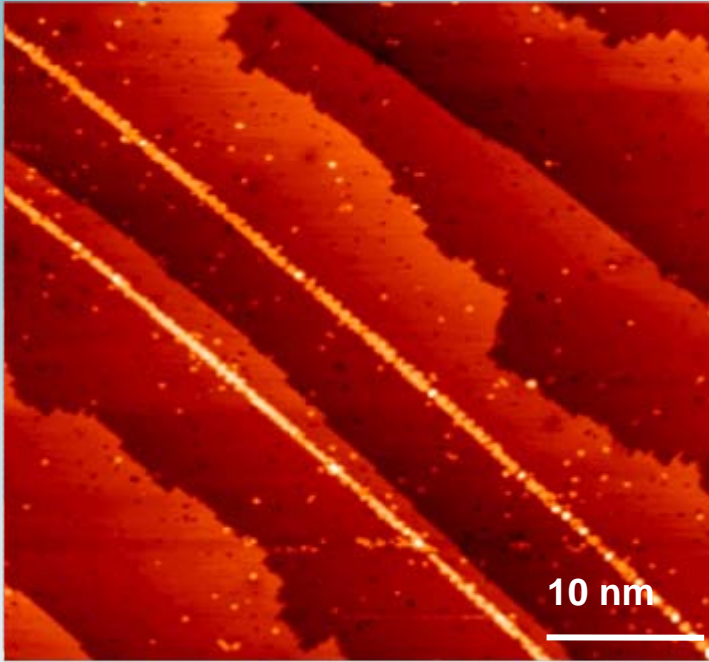
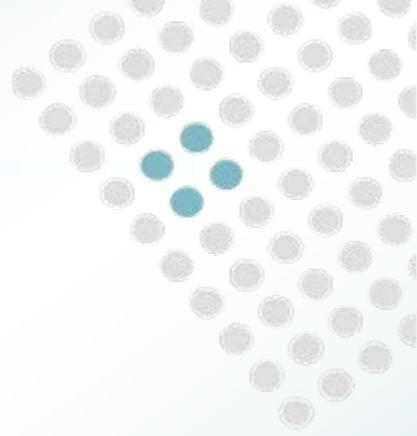


Sydney - UNSW



U Melbourne

Single Atom Nanoelectronics : Bottom Up



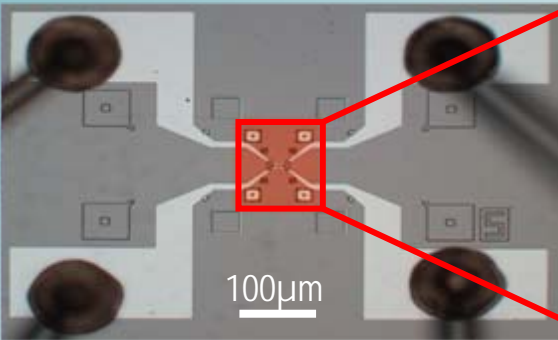
UNSW

M.Y. Simmons et al.

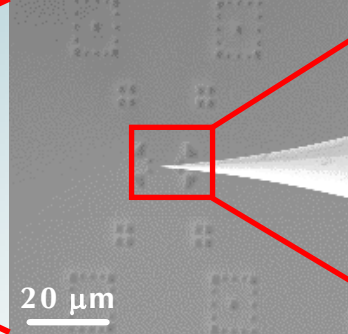
Single Atom Nanoelectronics : Bottom Up



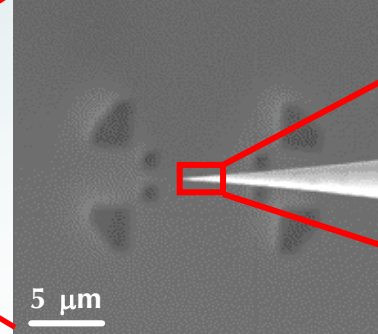
Optical Image



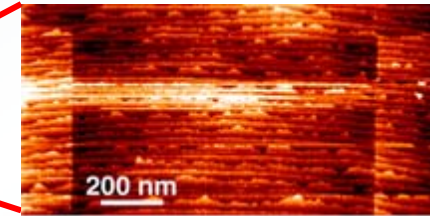
SEM Image



SEM Image



STM Image

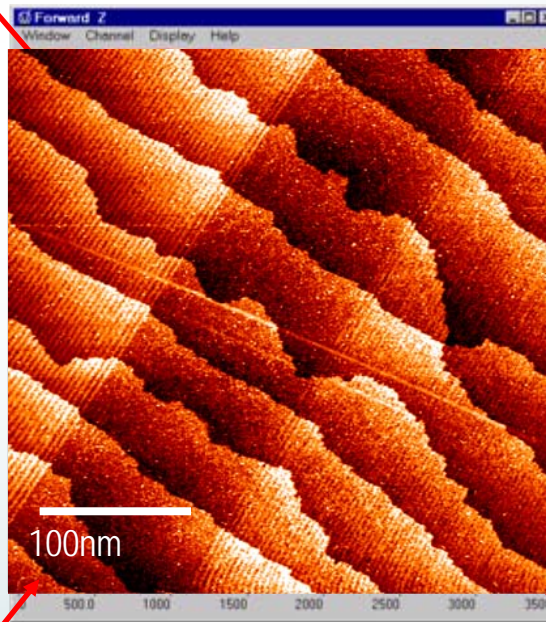


90 x 900nm



SEM Imaging

20 μm scan area

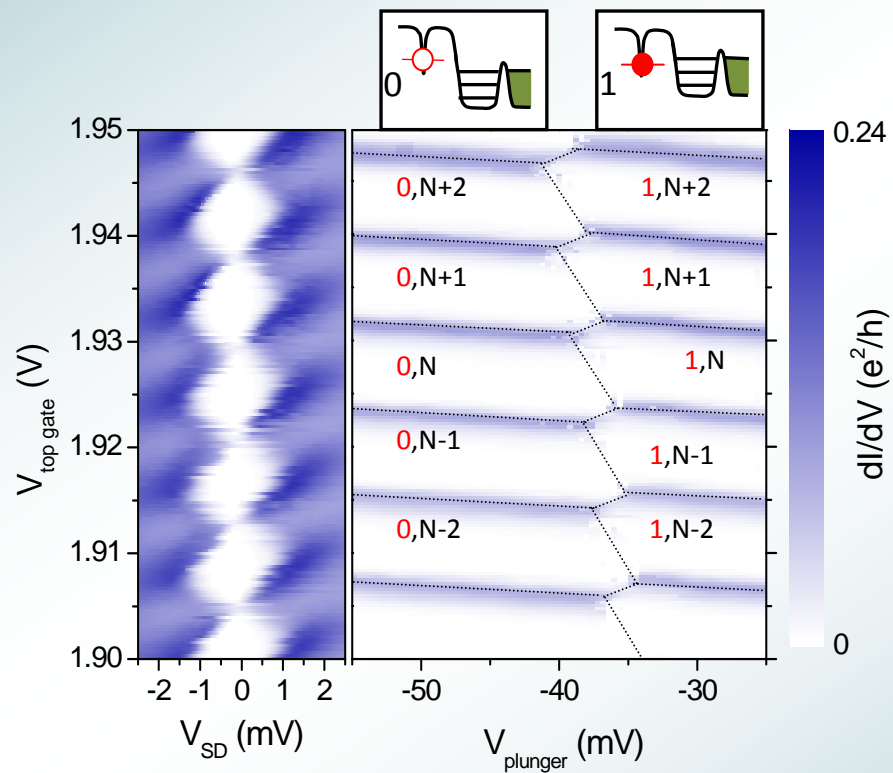
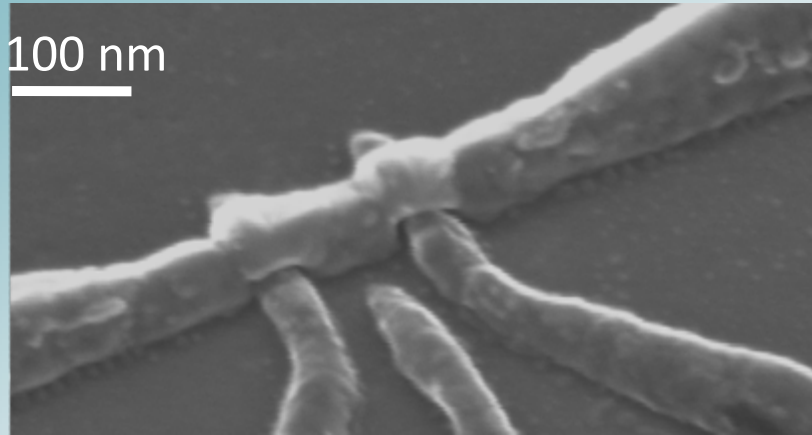


STM Imaging

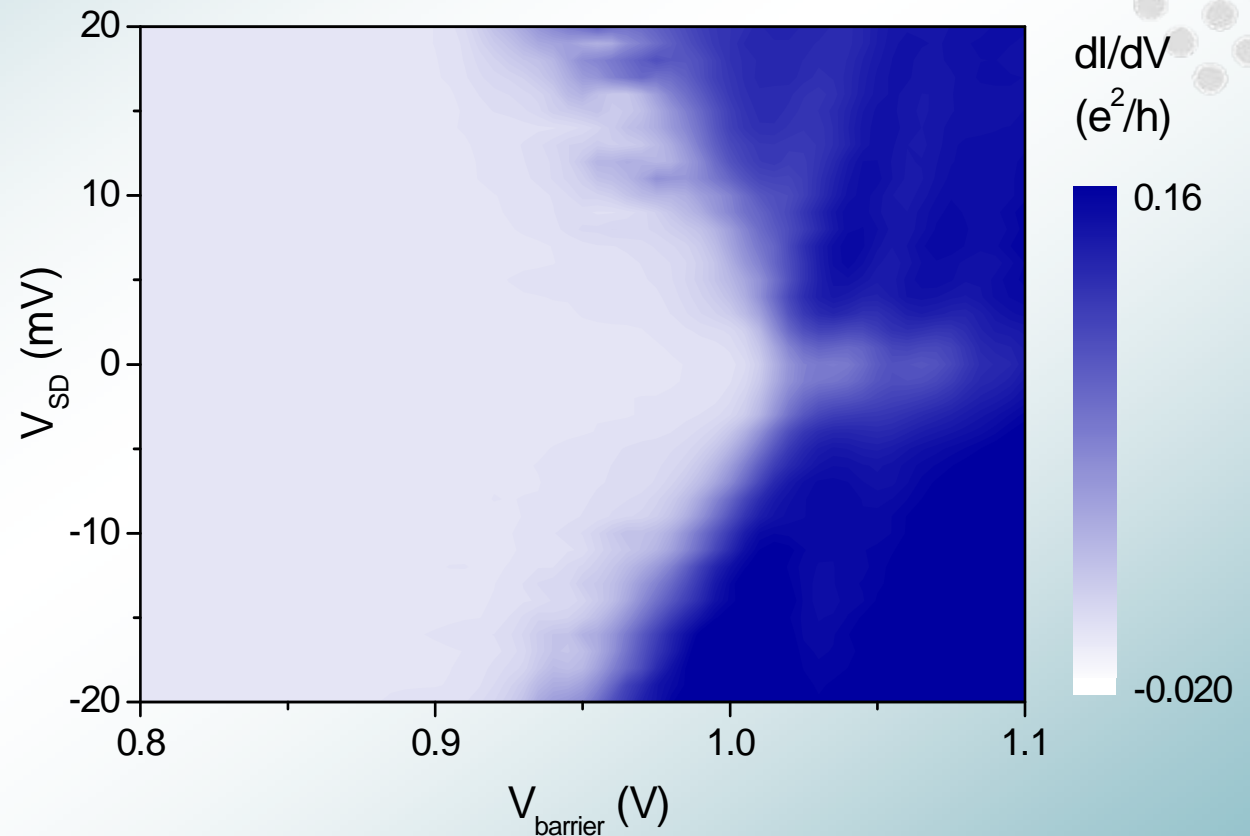
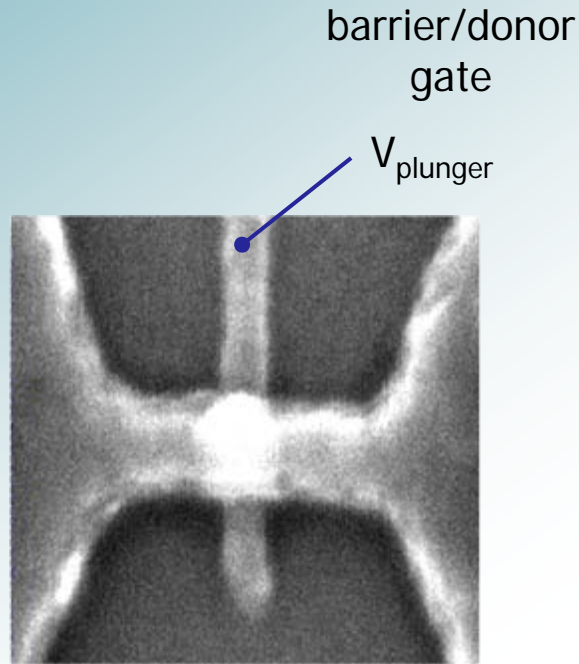
500 nm scan area

STM – Fabricated Device

Single Electron Electronics



Single Atom Transistor: Control Device



no P-implant \rightarrow no resonant tunneling features

Single Atom Transistor: P Atom Implants

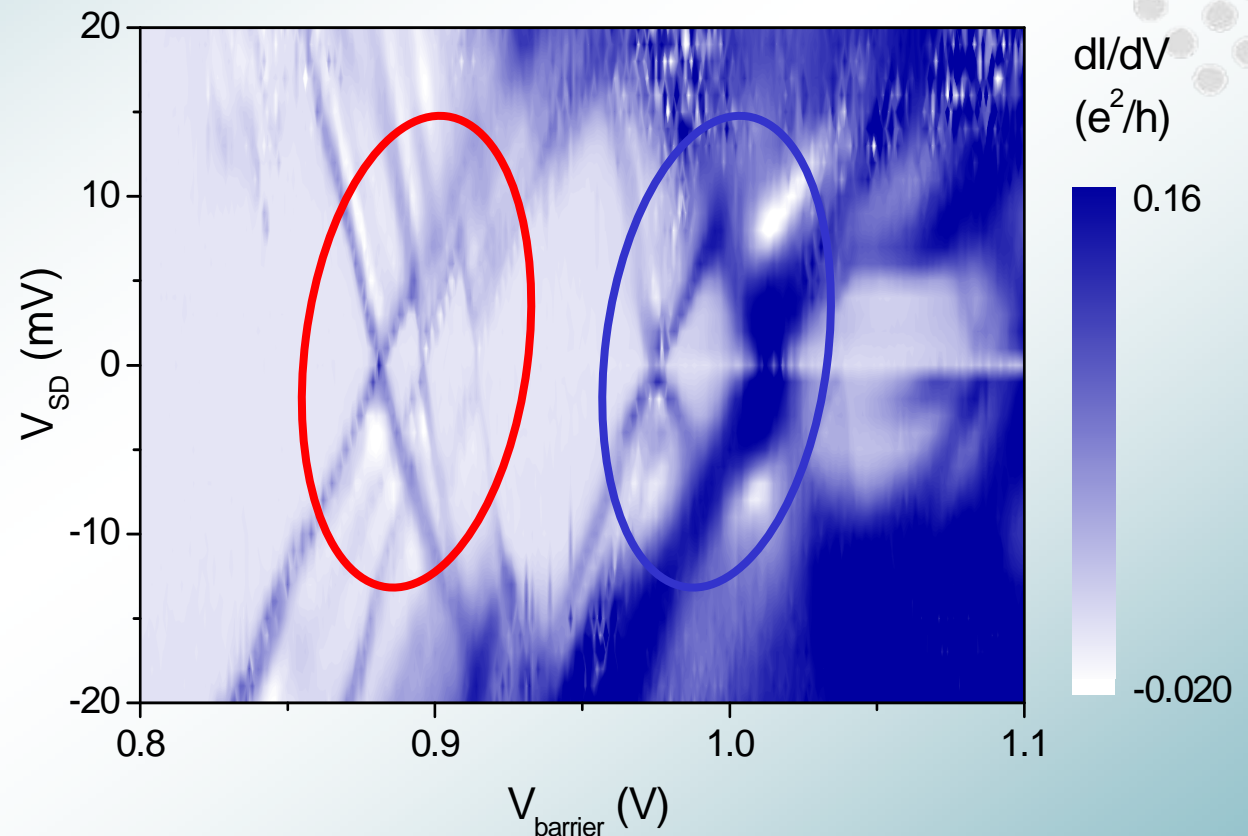
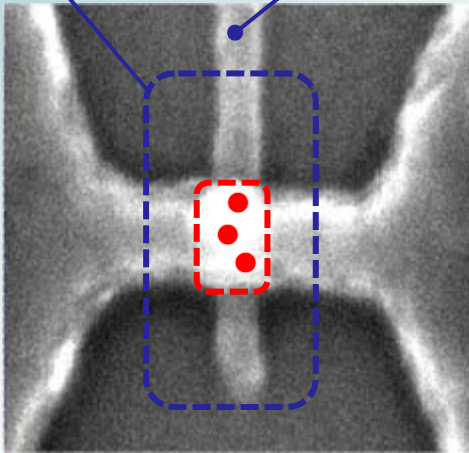
timed P-implant

$\langle n \rangle = 3$
in 50×30 nm

barrier/donor
gate

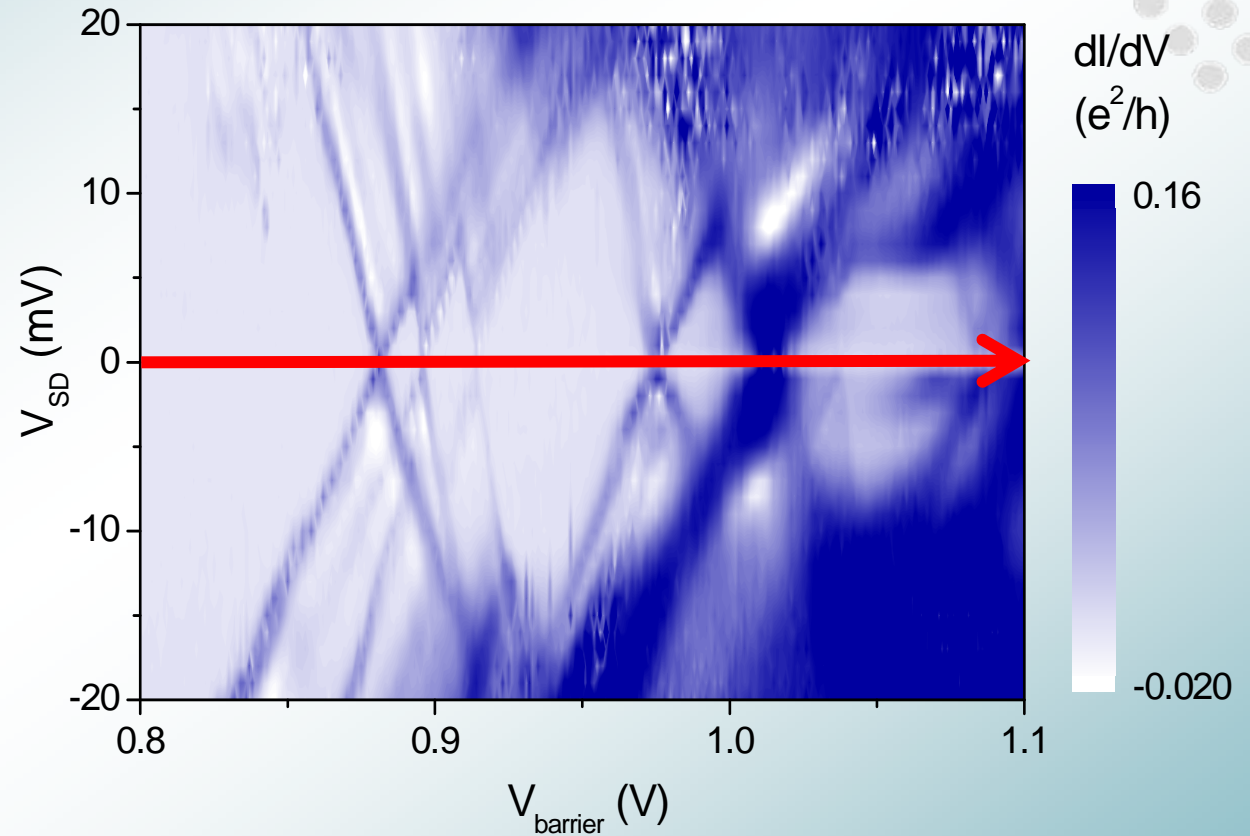
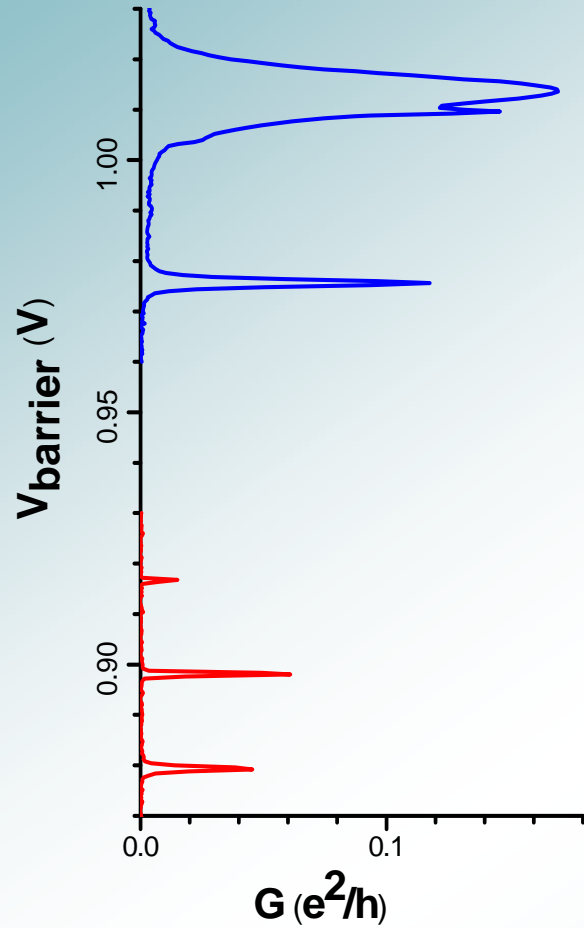
P-implant area

V_{plunger}

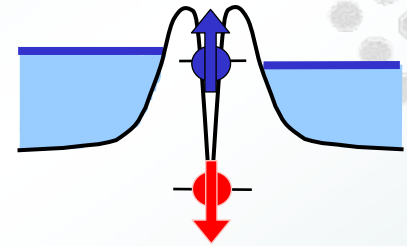
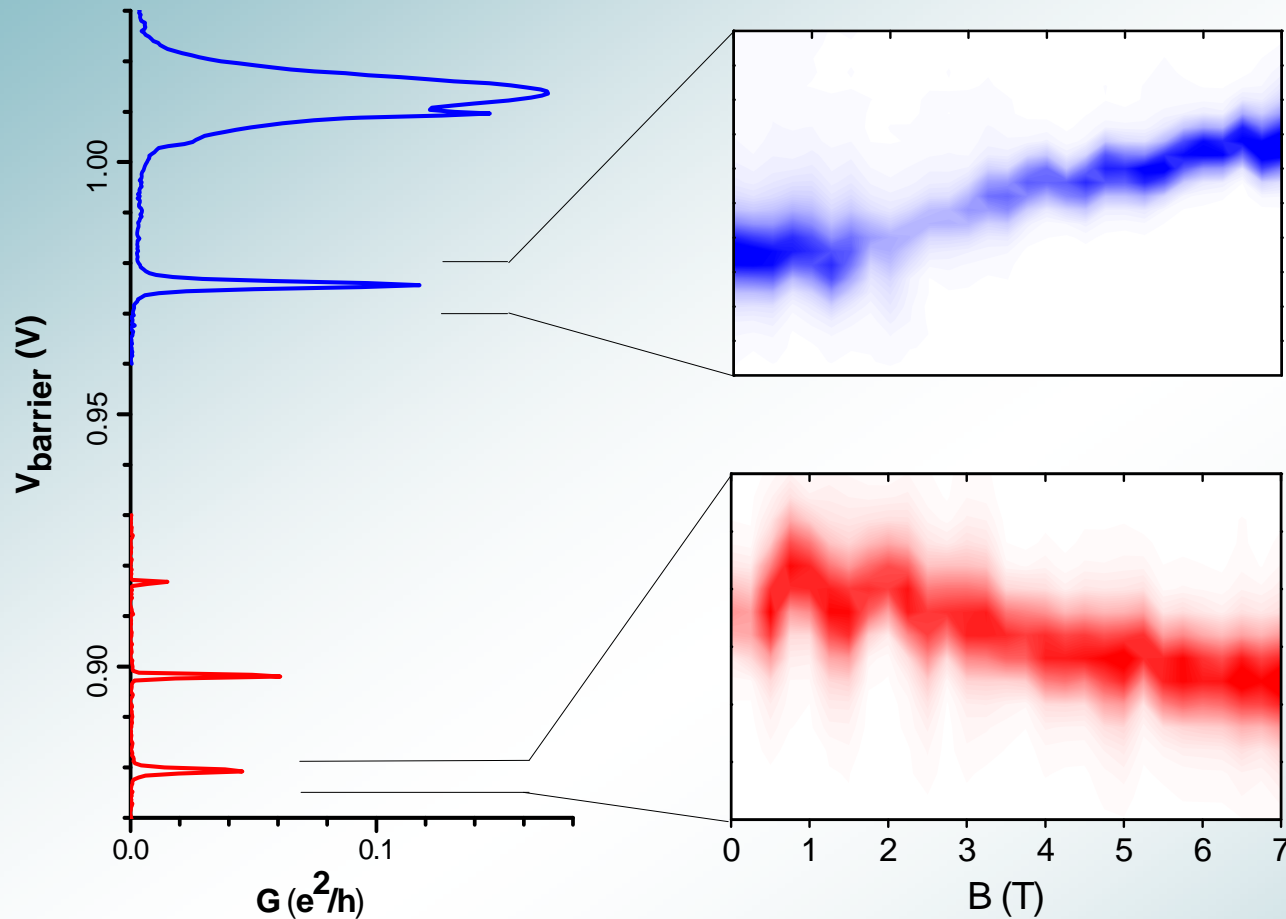


$\langle n \rangle = 3$ atoms \leftrightarrow 3 pairs of sharp resonant tunneling features

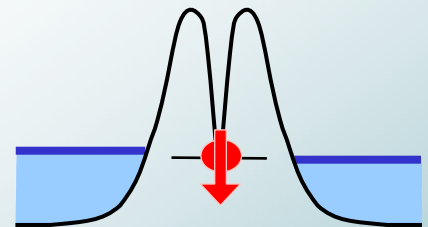
Single Atom Transistor: Tunneling Spectra



Zeeman Shift of P-Atom Electron States



Second electron on the donor
D⁻ state → spin-up



First electron on the donor
D⁰ state → spin-down

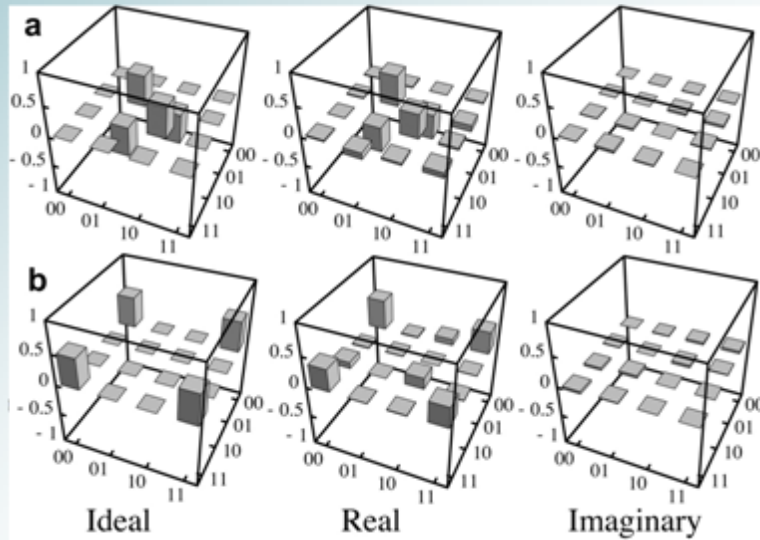
Resolved the Zeeman shift on electron states of individual donors

Single Photon Photonics

Linear Optics Quantum Computing

Predicted

Experiment

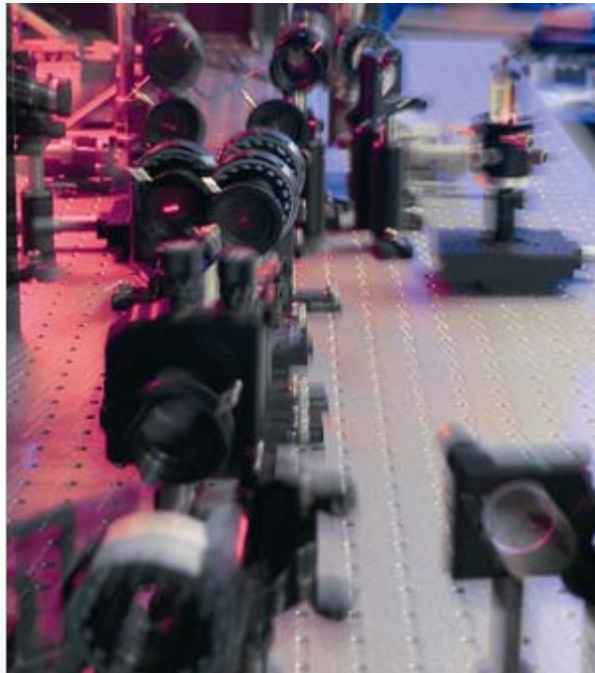


CNOT Gate

U Queensland

A.G. White et al.

Free Space & Fibre

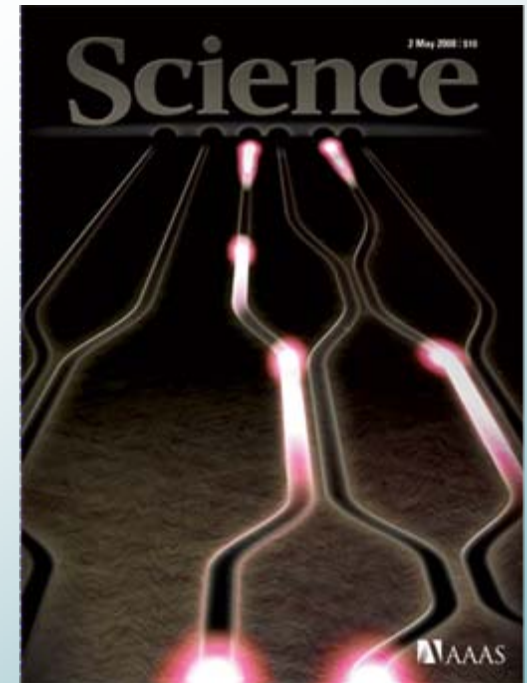


Polarisation or Frequency Encoding

U Queensland &

Australian Defence Forces Academy

Integrated Optics

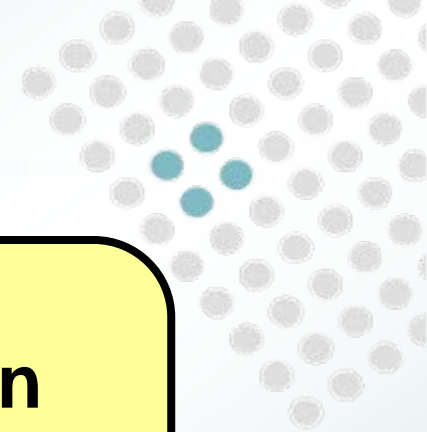


CNOT Gate

U Bristol

J.L O'Brien et al.

QIS – Key Application Areas



Data Security

National Security
Financial Services
e-Commerce

Decryption

National Security
Intelligence


Killer Apps

Supercomputers

Database Searching
Bioinformatics
Modeling & Design

Semiconductors

Integrated Circuits
Sensors
Nano-structuring

Secure Communications

- Quantum communication systems can be made **perfectly** secure (existing protocol BB84)
- Key applications (near to medium term):
 - Military & Security Services Communications
 - Financial Services
 - e-Commerce
 - Corporate Communications (sensitive data)
- Current data encryption market = **\$10 billion**
- Quantum LAN now available:
 - MagiQ (USA)
 - ID-Quantique (Switz)



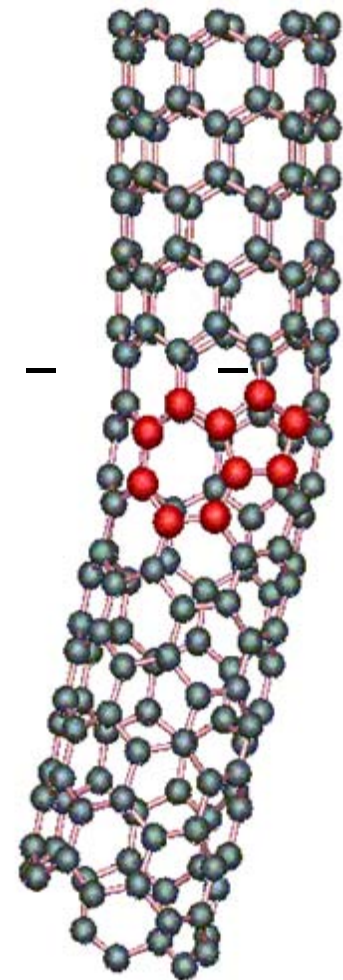
Code Decryption

- Public key encryption (RSA-129) is (almost) uncrackable.
Basis of public secure comms today
- A full-scale (few hundred qubits) quantum computer could crack RSA-129 in seconds (Peter Shor – 1994)
- Obvious applications in national and global security



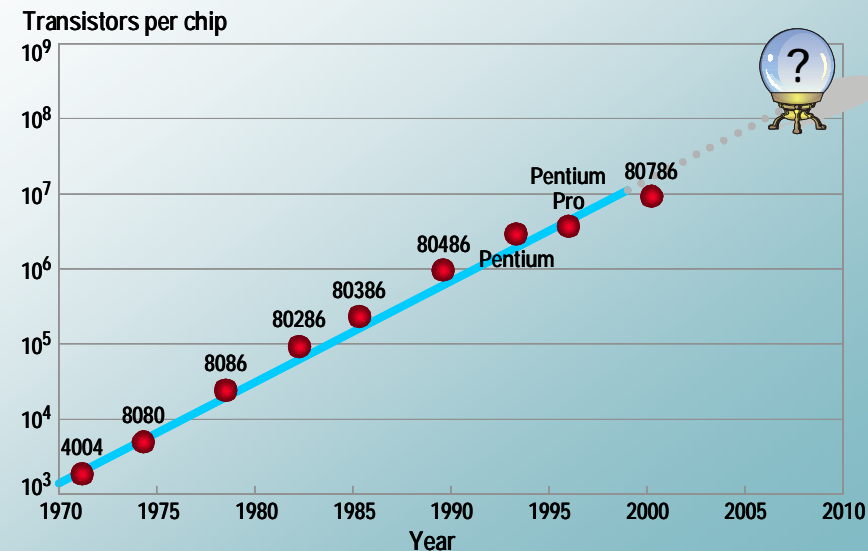
High Performance Computing

- Simulation (modeling) & database searching
- Existing supercomputers now under strain
- Application areas:
 - Nuclear weapons simulation
 - Rapid data search – Security services
 - Biotechnology
 - modeling (new reagents & pharma)
 - searching (bioinformatics)
 - Advanced R&D
 - modeling (commercial, govt)
 - Internet Search Engines
 - *q*Google ?
- Longer term prospect (15 – 30 years)



Next Generation Integrated Circuits

- Spin-off or pathway technologies potentially provide nearer term applications than QC per se
- Eg: Single atom nanotechnologies
- Possible applications:
 - Next generation transistors
 - extending Moore's Law (to 2020)
 - single atom transistors
- Current world semiconductor market \Rightarrow **\$200 billion**



CQCT: Key International Collaborations



Major International QC Projects



World Total = US\$180m p.a.*

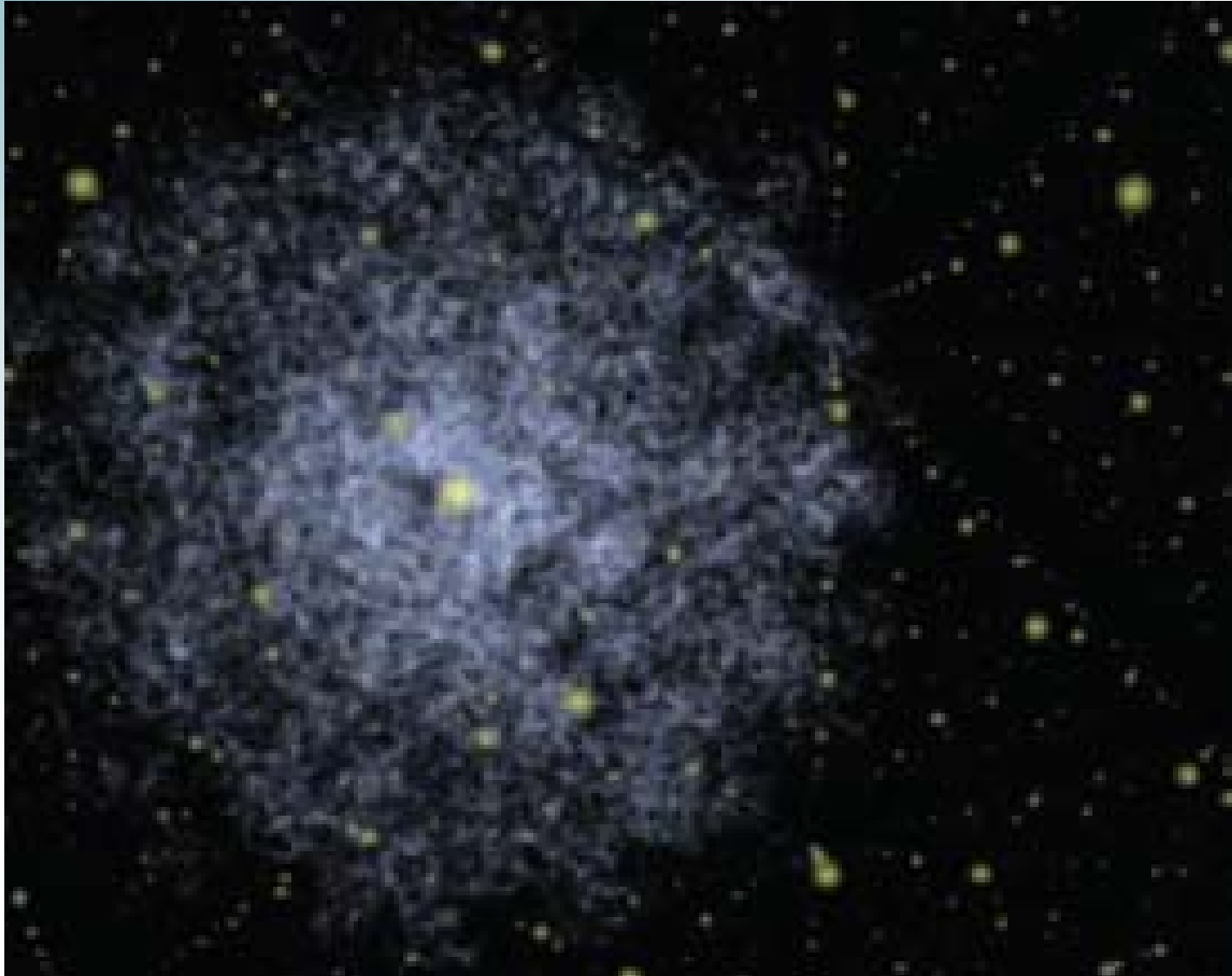


Summary – Quantum Information Science



- Quantum information technologies now a reality
- First impacts will be secure communications:
 - local area networks (0 – 5 years)
 - q -Internet & satellite comms (5 – 15 years)
- Longer term (15 – 30 years) quantum computing:
 - high-end computing (simulation, biotech)
- High risk, high pay-off technologies ...

Visualizing a Silicon Quantum Computer



See: Barry Sanders, Lloyd Hollenberg et al., in New Journal of Physics v10 (2008).
Barry Sanders, in Physics World, December 2008.